Experimental temperature/velocity control and implications for CFD

Presenters:
• Koji Yasutomi, Hino Motors Ltd
• Moez Ben Houidi, Pprime Institute, Poitiers, France
• Russ Fitzgerald, Caterpillar

Participants: All ECN community!
Motivation

- Do we know the initial conditions for Spray A?
  - What is the temperature distribution?
  - Is aerodynamics experimentally characterized?
  - How these parameters affect the spray results?

- What kind of initial boundary conditions should we use for CFD?
Motivation: Simulation to experiment comparison

VP and LL comparison from Topic 3

- Small different behavior can be observed when comparing experiments from different ECN facilities
- Simulation is not always perfectly predictive
Motivation: Simulation to experiment comparison

ID and LOL comparison from Topic 4/5

- Under-prediction of shock tube data result in a better match with experimental results
- Simulations use different chemistry and turbulence models
- Simulations are performed with a uniform ambient temperature hypothesis
- What about initial turbulence kinetic energy (not specified by experiments)?
- How does uniform T and velocity assumptions affect simulation to experiment comparison?
Motivation: Simulation with non-uniform T

- Injector protrudes into vessel 1.1 mm.
- Smallest cell size 0.125 mm.

CONVERGE with homogenous-cell chemistry
ECN 3.0 Yuanjiang Pei and Sibendu Som
Motivation: Simulation with non-uniform T

Time = 0.0 ms

ECN 3.0 Yuanjiang Pei and Sibendu Som

- Actual T delays ignition
- Asymmetric flame found in simulation, but not systematically observed in experiments yet (*SAE Paper, 2010-01-2106*)

<table>
<thead>
<tr>
<th>% change</th>
<th>900 K</th>
<th>1100 K</th>
</tr>
</thead>
<tbody>
<tr>
<td>Liquid length</td>
<td>17.23</td>
<td>27.5</td>
</tr>
<tr>
<td>Ignition delay</td>
<td>16.0</td>
<td>6.0</td>
</tr>
<tr>
<td>Lift-off length</td>
<td>5.3</td>
<td>8.1</td>
</tr>
</tbody>
</table>

- Retarded ignition will make the ignition delay predictions even worse in topic 2!

Better chemical mechanism!!
At X = 2 mm, T decrease after injection which indicates that colder gas near the boundary layer is pulled in.

Temperature measurement during the injection (inert condition in the RCM of Pprime Institute)

- Injection aerodynamic bring colder gas into the spray (~43K lower)
Initial boundary conditions can affect the spray characteristics

- Review temperature measurement in ECN facilities
- Collect boundary conditions (temperature and velocity) results from current ECN studies
- Try to understand their effects on spray and combustion

Discuss new recommendations for ECN spray A
### Review of temperature measurement techniques

<table>
<thead>
<tr>
<th>Method</th>
<th>Temperature range Min / Max(°C)</th>
<th>Response / transient capability</th>
<th>Accuracy</th>
<th>Commercially available / relative cost</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rayleigh scattering</td>
<td>20 / 2500</td>
<td>Very fast / no</td>
<td>1%</td>
<td>No / very high</td>
</tr>
<tr>
<td>Raman scattering</td>
<td>20 / 2227</td>
<td>Very fast / no</td>
<td>7%</td>
<td>No / very high</td>
</tr>
<tr>
<td>CARS (Coherent Anti-Stokes Raman Scattering)</td>
<td>20 / 2000</td>
<td>Fast / NA</td>
<td>5%</td>
<td>Yes / very high</td>
</tr>
<tr>
<td>LIF (Laser Induced Fluorescence)</td>
<td>0 / 2700</td>
<td>Very fast / no</td>
<td>10%</td>
<td>No / very high</td>
</tr>
<tr>
<td>Thermographic phosphors</td>
<td>-250 / 2000</td>
<td>Very fast / yes</td>
<td>0.1%-5%</td>
<td>Yes / high</td>
</tr>
</tbody>
</table>

#### Noninvasive methods

#### Semi-invasive

### Challenges

- **CVP**
  - Minor species in post-preburn => may cause fluorescence quenching

- **CPF/RCM/RCEM/Engines**
  - O₂ quenching
  - Low quantum yield at high temperature levels
  - Calibration of the technique may be mandatory especially at such high density and temperature levels

Optical methods can provide good spatial and temporal resolution however, they need prior development and a specific calibration for the quantitative measurement => expensive and difficult to install

*P.R.N. Childs, J.R. Greenwood and C.A. Long, Review of temperature measurement, Review of scientific instruments, volume 71, Number 8, August 2000*
<table>
<thead>
<tr>
<th>Invasive method</th>
<th>Temperature range Min / Max(°C)</th>
<th>Response / transient capability</th>
<th>Accuracy</th>
<th>Commercially available / relative cost</th>
</tr>
</thead>
<tbody>
<tr>
<td>Thermocouple</td>
<td>-270 / 2300</td>
<td>Very fast / yes</td>
<td>±0.5-±2°C</td>
<td>Yes / very low</td>
</tr>
</tbody>
</table>

- Thermocouples are cost-effective and accurate temperature sensors
- Can be used in all ECN combustion facilities
- Thermocouples might have a catalytic effect in oxidizing environment (type R for instance)
- Thermocouples might be altered by oxidation (this can have a significant effect on emissivity)
Review of temperature measurement techniques

Sheathed thermocouples

- + long lifespan (minimized long term drift under cycling conditions)
- + wires protected: can be used in corrosive environment with flowing materials (high robustness)
- - Slow response time

Bare-bead thermocouples

- + junction isolated from ground (avoid interference with instruments)
- + faster response time
- - shorter lifespan
- - Inherently brittle

<table>
<thead>
<tr>
<th>Ungrounded junction</th>
<th>Grounded junction</th>
</tr>
</thead>
<tbody>
<tr>
<td>junction protected</td>
<td>difference in thermal expansion between the sheath and junction materials may cause severe mechanical stress</td>
</tr>
<tr>
<td>junction isolated from ground</td>
<td>Ground loops may cause interference with instruments</td>
</tr>
<tr>
<td>defects in insulation may be easily detected</td>
<td>are more difficult to detect</td>
</tr>
<tr>
<td>slow response time</td>
<td>faster response time</td>
</tr>
</tbody>
</table>
**Why is response time too slow?**

Measured temperature $T_j$ depend on heat conduction from the sheath to the junction through the insulation and the thermocouple wires => thermal inertia does not only depend on the size of the junction but on the ensemble {sheath (s), insulation (i), junction(j) and wires (w) }

In such configuration, thermal conduction in the axial direction of the sheath has a significant impact on measured temperature.

Assuming that heat transfer is purely in the axial direction under steady state conditions, the axial heat flow may be modeled: $\lambda$ is thermal conductivity and $A$ is cross sectional area.

\[
Q_x = -\widetilde{\lambda A} \frac{dT}{dx}
\]

\[
\widetilde{\lambda A} = \lambda_w A_w + \lambda_i A_i + \lambda_s A_s
\]
Response compensation of fine wire thermocouples

The frequency response of such thermocouple configuration is extensively modeled in literature (energy balance + temperature expressed as Fourier integrals)

Schematic of bare-bead ungrounded fine wire thermocouple

Hypothesis:
• Fine wires: temperature radially homogeneous => conduction is considered in axial direction x (for instance when T prongs is lower than T wires)
• Heat transfer through: catalytic reactions on the junction, viscous dissipation and thermoelectric effects are neglected

Recommendations to minimize conduction effects: $L >> d_2$ and $d_2 = d_1$

Simulated frequency response of a 25µm type K thermocouple with various probe configurations
Recommendations for the thermocouples design

\[
\frac{L}{l_c} > 10 \approx \frac{L}{d_2} \geq 400
\]

\(d_1\) and \(d_2\) as small as possible

TU/e, type R
\(d_w = 50 \, \mu m\)
\(d_j = 100 \, \mu m\)

Prisme (Orleans, France), type K
\(d_w = 13 \, \mu m\)
\(d_j = 39 \, \mu m\)

Pprime (Poitiers, France), type K
\(d_w = 7.6 \, \mu m\)
\(d_j = \sim 8 \, \text{to} \, 14 \, \mu m\)

Review of error correction / response compensation

\[ T_g = T_j + \tau \frac{dT_j}{dt} + \frac{\sigma \varepsilon}{h} (T_j^4 - T_s^4) \]
\[ \tau = \frac{\rho_j C_j d_j}{4h} \]

Collis and Williams for 0.02 < Re < 44:

\[ Nu = (0.24 + 0.51Re^{0.45}) \left( \frac{T_f}{T_g} \right)^{0.17} \]
\[ T_f = \frac{T_j + T_g}{2} \]
\[ h = \frac{Nu \lambda_g}{d} \]

\( C_j = f(T_j) \) and \( \varepsilon = f(T_j) \)

\( h = f(T_f, \rho_f, \nu) \); thermal conductivity and dynamic viscosity of surrounding gas at film temperature \( T_f \)

Main issue is to find a good estimation of the cross flow velocity through the junction

- Using a 12.7 µm wire instead of 7.6 µm double the correction (measured temperature increase rate \(~17.6 \text{ K/ms})
- 1 m/s under-estimation of velocity \( \Rightarrow \) 6 K higher correction (example of a type K 12,7µm wire thermocouple, measured temperature increase rate \(~17.8 \text{ K/ms})
- 1000 W/m².K under-estimation of h (heat coefficient) \( \Rightarrow \) 2 K higher correction (example of a type K 12,7µm wire thermocouple, measured temperature increase rate \(~17.6 \text{ K/ms})
Spatial heterogeneities from available data

- Temperature heterogeneities are observed in all facilities
- How to calculate the density?

[Sandia data are presented by distribution of $T_{core}$ measured/$T_{core}$ predicted]
Spray A ID and LOL results

Prisme and Pprime: RCM
Sandia, IFPEN, TU/e: CVP
Temperature distribution is uniform on horizontal, except near the cold injector

- At < 10 mm from injector, $T$ decreases
- But lift-off length is only 16 mm
Temperature drop at the thermal boundary is less effect at the GM and CAT case, but we doubt the accuracy of collection.
Limitations of sheath TC measurements.
Incorporate corrections.
Sandia vessel observe the highest variance only in thermal boundary layer.
The red is set at 0.8mm from laser entrance window—much lower than the measurements in the core, and much higher frequency. Suggests that if the injector were flush mounted, the temperature would be much less uniform.
What are the actual temperature and velocity distributions?
Array of 24 thermocouples arranged to characterize vessel temperature:

- K-type
- 1mm sheath
- Threaded through port opposite injector holder

Measurements in multiple planes:

- Three vertical planes at varying axial distances
- Vertical and horizontal planes containing injector axis
Temperature Distribution in Caterpillar Constant Pressure Vessel

April 2017

ECN5
Temperature Distribution in Caterpillar Constant Pressure Vessel

April 2017
Velocity Measurements in Caterpillar Constant Pressure Spray Vessel

Objectives:
- Measure mean velocity flowfields
- Quantify spatially varying turbulent fluctuations and length scales

Approach:
8Hz LaVision PIV system.
Seed flow with Superfine ZrO$_2$ Powder (500nm)
  - Density controlled by downstream orifice and supply pressure
  - Timing optimized to minimize flow disturbance and maximize signal

Acquire planar images at several distances from injector tip location
200 shots / image pairs acquired for flow field convergence.
Several magnifications and fields of view used to verify turbulent intensity and length scales.

Test Conditions

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Values</th>
</tr>
</thead>
<tbody>
<tr>
<td>$P_{HTPV}$ [bar]</td>
<td>60, 120</td>
</tr>
<tr>
<td>$T_{HTPV}$ [K]</td>
<td>800, 900, 1000</td>
</tr>
<tr>
<td>Sheet Location [mm]</td>
<td>10, 18, 24, 49, 75, 88</td>
</tr>
<tr>
<td>Lens [mm] (magnification)</td>
<td>50, 105, 200</td>
</tr>
</tbody>
</table>
Simulated Vapor Penetration is Sensitive to Assumed Initial Turbulence

- Model overpredicts penetration for zero initial TKE
- Model underpredicts jet penetration for high initial levels of TKE.

What initial turbulence parameters should be used for spray simulations?

What are the background turbulence levels in spray vessels and how do they vary?
Modest effects of ambient temperature and pressure
Low bulk horizontal fluid motion; local max near center
Bulk vertical fluid motion same order as in/out flow; maximum near cold injector holder
Isotropic turbulence near vessel centerline
Vertical turbulent component increases quickly near injector holder

Velocity Measurements Exhibit Consistent Trends Over Range of Conditions
Mean Velocity and Turbulence Levels Reflect Differences in Spray Vessel Type

- Constant volume pre-burn vessel has lowest mean velocities
- Caterpillar constant mean velocities are higher; still represent very small displacement during injection
- TKE in both vessels is low; Caterpillar vessel turbulence is higher; simulations needed to determine computational significance
- Lingering questions:
  - Isotropy
  - Turbulent length scale

### Mean Velocities

<table>
<thead>
<tr>
<th></th>
<th>Caterpillar Constant Pressure Vessel</th>
<th>Sandia Constant Volume Vessel (1000 rpm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mean Velocities:</td>
<td>*0.12m/s (.110/.055)</td>
<td>0.03m/s (.028/.008)</td>
</tr>
<tr>
<td>Velocity Fluctuations:</td>
<td>0.07m/s (.065 / .077)</td>
<td>0.018m/s (.017,.020)</td>
</tr>
<tr>
<td>Turbulent Kinetic Energy:</td>
<td>0.008m²/s²</td>
<td>0.0005 m²/s²</td>
</tr>
<tr>
<td>Turbulent Length Scale:</td>
<td>10-15mm</td>
<td>unknown</td>
</tr>
</tbody>
</table>

*Corresponds to 0.5mm displacement during 5ms injection

\[
RMS = \sqrt{\frac{1}{N-1} \sum_{i=1}^{N} (V_i - \bar{V})^2}
\]

\[
\bar{V} = \frac{1}{N} \sum_{i=1}^{N} V_i
\]

\[
TKE = \frac{1}{2} \left( RMS_x^2 + RMS_y^2 + \left( \frac{RMS_x + RMS_y}{2} \right)^2 \right)
\]
Velocity effect on temperature field?

Spray H conditions. 8000rpm 14.8kg/m3

Spray A conditions. 1000rpm 22.8kg/m3

➢ Higher fan speed shows more uniform temperature fields
Faster cooldown DOES correspond to higher velocity and turbulence (Similar surface area to volume ratio in these chambers)
Fan speed affect to Initial turbulent kinetic energy.

What is the effect of TKE to spray?
Comparison of cool down Sandia (500,900,1200 rpm), TUE (2000 rpm)

- Higher Fan speed => higher amplitude fluctuation at low frequencies
Ignition delay and LOL are described by temperature, not the “Fan speed”
Velocity effect to the Soot (Spray A fan speed sweep)

- Temperature field pocket → Ignition delay and Lift-off length → Soot
- Spray characteristics do not change
Near the injector window, temperature drop is significant especially for constant volume chamber.

Constant pressure chamber showed slightly high TKE about 0.008 than constant volume vessel about 0.0005m/s

SUGGESTIONS for modeler

- Please use the non-uniform temperature distribution!!
  (We are not ready to propose the “one” temperature distribution which can explain the whole facility)
- To apply the TKE to simulation is also important to get “actual temperature” fields.
Acknowledgements

- Thanks Panos Sphicas (IC), Scott Skeen (Sandia), Scott Parrish (GM), Noud Maes (Tue), Michele Bardi (IFPEN), Ob Niphalai (Prisme), Tiexua (CMT) and Russ Fitzgerald (Caterpillar) for providing the temperature and velocity data of the vessel.

- Thanks Lyle Pickett, Gilles Bruneaux and Raul Payri for encouraging for this topic session.
Backup Slides
Determination of Velocity Statistics

Vertical Plane: 24mm from Injector Tip
Pa = 60bar, Ta = 900K
Δt = 800µs, 50mm lens

Instantaneous Velocity
\[ U = \bar{U} + U' \]

Mean Velocity \( \bar{U} \)

Velocity Fluctuations \( U' \)
Characteristics of HTPV Turbulence

- Seeder adds some turbulence; need to carefully analyze data ‘after settling’
- Turbulence appears to be homogeneous and isotropic
- ‘Good vectors’ crucial for good turbulence statistics.
- Turbulence intensity is on the order of 25-30%
### Review of error correction / response compensation

<table>
<thead>
<tr>
<th></th>
<th>Tck7</th>
<th>Tc</th>
<th>Tg7_Nu</th>
<th>Tg7_Nu_m</th>
<th>Tg7_Nu_ma</th>
</tr>
</thead>
<tbody>
<tr>
<td>effect of velocity</td>
<td>Vmeasured</td>
<td>0.05</td>
<td>1</td>
<td>m/s</td>
<td></td>
</tr>
<tr>
<td></td>
<td>930</td>
<td>936</td>
<td>936</td>
<td>939</td>
<td>934</td>
</tr>
<tr>
<td></td>
<td>9</td>
<td>4</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th></th>
<th>Tck12</th>
<th>Tc</th>
<th>Tg12_Nu</th>
<th>Tg12_Nu_m</th>
<th>Tg12_Nu_ma</th>
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</thead>
<tbody>
<tr>
<td>effect of velocity</td>
<td>Vmeasured</td>
<td>2</td>
<td>3</td>
<td>m/s</td>
<td></td>
</tr>
<tr>
<td></td>
<td>830</td>
<td>873</td>
<td>869</td>
<td>872</td>
<td>866</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>42</td>
<td>39</td>
<td></td>
</tr>
</tbody>
</table>

- **dTj/dt = ~ 17k/ms**

<p>| | | | | | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>TU/e, type R</td>
<td>d_w = 50 µm</td>
<td>d_j = 100 µm</td>
<td>Correction (SOI) = ~ 23 K</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Prisme (Orleans, France), type K</td>
<td>d_w = 13 µm</td>
<td>d_j = 39 µm</td>
<td>Correction (SOI) = ~ -21 to 28 K</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Pprime (Poitiers, France), type K</td>
<td>d_w = 7.6 µm</td>
<td>d_j = ~ 8 to 14 µm</td>
<td>Correction (SOI) = ~ -1 to 8 K</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
# Review of temperature measurement in ECN facilities

## Comparison of data from literature

<table>
<thead>
<tr>
<th>Institution</th>
<th>Facility</th>
<th>Thermocouple type</th>
<th>Wires dimension</th>
<th>Error corrections</th>
<th>Conduction error neglected</th>
<th>Hypothesis</th>
<th>Convection</th>
<th>Radiation</th>
<th>Total correction</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sandia SNL</td>
<td>CVP</td>
<td>Type-R : Pt/Pt+13Rh</td>
<td>50 µm</td>
<td>Conduction error neglected</td>
<td>yes</td>
<td></td>
<td>yes</td>
<td>yes</td>
<td>4 to 10 K (around 900 K)</td>
</tr>
<tr>
<td>TU/e</td>
<td>CVP</td>
<td>Type-R : Pt/Pt+13Rh</td>
<td>50 µm</td>
<td>Conduction error neglected</td>
<td>yes</td>
<td></td>
<td>yes</td>
<td>yes</td>
<td>4 to 10 K (around 900 K)</td>
</tr>
<tr>
<td>IFPEN</td>
<td>CVP</td>
<td>Type-K : Ni/Cr</td>
<td>single 50 µm or 25 µm?</td>
<td>Conduction error neglected</td>
<td>no correction</td>
<td>yes</td>
<td>yes</td>
<td>yes</td>
<td>4 to 10 K (around 900 K)</td>
</tr>
<tr>
<td>Caterpillar</td>
<td>CPF</td>
<td>Type-K : Ni/Cr</td>
<td>1 and 3 mm</td>
<td>* Temperature is homogeneous in the small volume where the different thermocouples with different diameters are placed * Temperature is averaged over 10 s</td>
<td>no correction</td>
<td>no correction (temperature averaged over time)</td>
<td></td>
<td></td>
<td>?</td>
</tr>
<tr>
<td>CMT</td>
<td>CPF</td>
<td>Type-K : Ni/Cr</td>
<td>?</td>
<td>* Temperature is homogeneous in the small volume where the different thermocouples with different diameters are placed * Temperature is averaged over 20 s</td>
<td>no correction</td>
<td>no correction (temperature averaged over time)</td>
<td></td>
<td></td>
<td>?</td>
</tr>
<tr>
<td>Pprime</td>
<td>RCM (single shot)</td>
<td>Type-K : Ni/Cr</td>
<td>7.6 µm</td>
<td>Conduction error neglected</td>
<td>yes</td>
<td></td>
<td>yes</td>
<td>yes</td>
<td>2 to 4 K (around +10 ms relative to SOI)</td>
</tr>
</tbody>
</table>

\[
T_g = T_j + \text{conduction error} + \frac{\alpha T_j}{\frac{dT_j}{dt} + \frac{\tau}{h} (T_j - T_w)}
\]

\[
\tau = \frac{\rho \lambda d_x}{4h}
\]
## Review of temperature measurement in ECN facilities

### Comparison of data from literature

<table>
<thead>
<tr>
<th>Institution</th>
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<th>Thermocouple type</th>
<th>Wires dimension</th>
<th>Wall temperature</th>
<th>Heterogeneity level</th>
<th>reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sandia SNL</td>
<td>CVP</td>
<td>Type-R : Pt/Pt+13Rh</td>
<td>50 µm</td>
<td>461 K</td>
<td>* Std at 40 mm downstream of spray axis: 11 K&lt;br&gt;* 45 K lower near the injector holder&lt;br&gt;* +-1% variation in spray axis&lt;br&gt;* +-4% variation in vertical axis ++15 mm</td>
<td>1- Meijer et al. Atomization and sprays, 22 (9) 2012&lt;br&gt;2- Pickett et al. SAE 2010-01-2106</td>
</tr>
<tr>
<td>TU/e</td>
<td>CVP</td>
<td>Type-R : Pt/Pt+13Rh</td>
<td>50 µm</td>
<td>443 K</td>
<td>* Std at 40 mm downstream of spray axis: 12 K</td>
<td>1- Meijer et al. Atomization and sprays, 22 (9) 2012&lt;br&gt;2- Pickett et al. SAE 2010-01-2106</td>
</tr>
<tr>
<td>IFPEN</td>
<td>CVP</td>
<td>Type-K : Ni/Cr</td>
<td>single 50 µm or 25 µm?</td>
<td>473 K</td>
<td>* Std at 40 mm downstream of spray axis: 14 K&lt;br&gt;* +-2% variation in spray axis&lt;br&gt;* &lt; +-4% variation in vertical axis +15 mm</td>
<td>1- Meijer et al. Atomization and sprays, 22 (9) 2012&lt;br&gt;2- Pickett et al. SAE 2010-01-2106</td>
</tr>
<tr>
<td>Caterpillar</td>
<td>CPF</td>
<td>Type-K : Ni/Cr</td>
<td>1 and 3 mm</td>
<td>800 + 5 K</td>
<td>* 14 K lower near the injector holder (892 to 906 K within 3 mm from the injector)</td>
<td>1- Meijer et al. Atomization and sprays, 22 (9) 2012&lt;br&gt;2- Pickett et al. SAE 2010-01-2106</td>
</tr>
<tr>
<td>CMT</td>
<td>CPF</td>
<td>Type-K : Ni/Cr</td>
<td>?</td>
<td>800 + 5 K</td>
<td>* Std in center volume downstream of spray axis: 2,3 K (1 Hz logging)&lt;br&gt;* 10 K lower near the injector holder (895 to 905 K within 3 mm from the injector)</td>
<td>1- Meijer et al. Atomization and sprays, 22 (9) 2012&lt;br&gt;2- Pickett et al. SAE 2010-01-2106</td>
</tr>
<tr>
<td>Pprime</td>
<td>RCM (single shot)</td>
<td>Type-K : Ni/Cr</td>
<td>7,6 µm</td>
<td>363 K</td>
<td>* Std at 39 mm downstream of spray axis: 20 K&lt;br&gt;* spatial Std : 18 K</td>
<td>ECN France</td>
</tr>
</tbody>
</table>
Velocity data Pprime

*Average velocity field (time average 20 ms)*
*Maximum velocity 0.7 m/s*

Turbulence is estimated in the time window -10 to +10 ms after SOI. It is possible to recalculate TKE with smaller time range or with cyclic variations but at a lower density level.
Pprime RCM vs CMT RCEM

![Graph showing the comparison between Pprime RCM and CMT RCEM](image)